Stormwater Runoff Flow Control Benefits of Urban Drainage System Reconstruction According to Natural Principles

Richard R. Horner

University of Washington

Abstract

Seattle Public Utilities constructed two drainage projects to decrease stormwater quantities discharged to Pipers Creek, with the goal of reducing channel erosion and pollutant loadings. The Viewlands "Cascade" replaced a narrow ditch with a wide series of stepped pools. Reconstruction of approximately 65 ft (200 meters) of 2nd Avenue NW and its drainage system reduced impervious area and provided vegetated stormwater detention areas. At both sites flow has been continuously monitored in relation to precipitation to determine actual benefits. The Viewlands Cascade is capable of reducing the influent runoff volume by over one-third during the wetter months and overall for the year. Relative to estimates for the preceding ditch, the new channel reduces runoff discharged to Pipers Creek in the wet months by a factor of three. The 2nd Avenue NW project has prevented the discharge of all dry season flow and 98 percent of the wet season runoff. It can fully attenuate the runoff volume produced by approximately 0.75 inch (19 mm) of rain on its catchment. Relative to estimates for a conventional street design, the alternative reduces runoff discharged to Pipers Creek in the wet months by a factor of 4.7. The results demonstrate that "naturalizing" urban drainage systems can yield substantial benefits.

Background and Objectives

The City of Seattle has launched a program to protect and improve the health of the city's freshwater ecosystems. Creative approaches are necessary to manage stormwater in urban areas, since impacts from the developed watershed significantly influence the health of the stream. As such, the National Marine Fisheries Service (NMFS) requires quantitative relationships between stormwater management activities implemented in the watershed and benefits to the associated stream ecosystem. The Washington Department of Ecology (WDOE) is moving in the same direction under the city's stormwater National Pollutant Discharge Elimination System (NPDES) permit.

In the summer of 1999, Seattle Public Utilities (SPU) established a memorandum of understanding with the University of Washington's Center for Urban Water Resources Management to assist in the evaluation of various stormwater management Capital Improvement Projects (CIPs). The work under the agreement involves testing a variety of innovative "ultra-urban" stormwater management techniques and documenting their benefits with quantitative data. In this context "ultra-urban" is defined as any built environment within the city of Seattle, including a variety of industrial, commercial, residential, and mixed land use types. The first stormwater management projects proposed for testing apply mainly to single-family residential and neighborhood commercial areas.

The broad objectives of the series of ultra-urban studies are to:

1. Determine how effective the selected projects are in reducing peak rates and volumes of runoff.
2. Evaluate receiving water ecosystem benefits that could be achieved with widespread application of these project types.
3. Develop a long-term, systematic approach to ultra-urban stormwater management in Seattle.

The first two ultra-urban stormwater management projects to be evaluated were the Viewlands Cascades Drainage System and the 2nd Avenue NW Street Edge Alternative (SEA) Streets Millennium Project. The projects were designed to reduce stormwater quantities discharged to Pipers Creek. A related goal in the case of Viewlands was to decrease the high velocities often occurring in the previous drainage ditch to prevent bypass of the drain inlet at its end, and the consequent erosion of the adjacent slope. Both projects were also expected to provide water quality benefits through enhanced pollutant capture by vegetation and soils and reduced pollutant mass loadings associated with lower flow volumes.

The Viewlands Cascade receives drainage from a catchment originally thought to be approximately 26 acres (10.5 ha) in area. Collected runoff is piped to the Cascade, where it flows through 16 stepped cells formed by log weirs to the downstream drain inlet and onward to Pipers Creek via another pipe. Construction cost was approximately $225,000.

The 2nd Avenue NW SEA Streets project represents a full street right-of-way redesign. The width of the 660-ft (201-m) long roadway between NW 117th and NW 120th Streets was reduced from 25 ft (7.6 m) to 14 ft (4.3 m), parking slots were provided at angles to the street, and sidewalks were added. The remainder of the 60-ft (18-m) right of way was devoted to runoff detention ponds planted with native vegetation. The original right of way covered approximately 0.91 acre (0.37 ha), about 0.38 acre (0.15 ha) of asphalt and the remainder in vegetation on the edges. Hard surface was reduced slightly to 0.31 has (0.13 ha) in the redesign, with the remainder given to ponds. The construction cost was initially bid at $244,000. There were substantial additional costs for this first-of-its-type project in reaching community consensus, change orders to satisfy community concerns, etc. The catchment area draining to the 2nd Avenue NW pond system includes properties on the east side of 2nd Avenue NW, as well as the streetscape, and totals approximately 2.3 acres (0.93 ha).

A graduate thesis (Miller 2001) and a technical report drawn from the thesis (Miller et al. 2001) document all events in the ultra-urban stormwater management studies from setup of the stations in early 2000 through January 2001. These references provide more extensive background to the projects, a review of relevant literature, descriptions of the monitoring equipment and methods at both sites, data management and analysis procedures, results for the period of coverage, discussion of findings, and what conclusions could be drawn at that time. A second report (Horner et al. 2002) covers monitoring starting with the water year on October 1, 2000 at Viewlands, and at the conclusion of SEA Streets project construction in January 2001, through April 2002. This paper summarizes the results from both periods and draws some conclusions from the findings.

Brief Description of Instrumentation

This section provides a basic description of the monitoring systems established at both projects. Refer to Miller (2001) and Miller et al. (2001) for full details.

The log weirs at the ends of cells 1 and 15 of the Viewlands Cascades Drainage System were outfitted with V-notch weirs to serve as controls for comparative flow monitoring near the entrance and exit of the channel. Weir water levels, from which flow rates were computed, were sensed at each point with both float/shaft encoders and submersible pressure transducers.

The Viewlands site has a full meteorology station on the adjacent elementary school property. The station has three precipitation gauges, two tipping-bucket recording gauges and a non-recording collector. Mounted on a tripod are temperature and relative humidity probes, a wind anemometer, a net radiometer, a short-wave pyranometer, and a solar panel for power supply. The station also includes an evaporation pan with an anemometer and a radiometer mounted just above the water surface. Data from all flow and meteorological instruments are logged at one of three data loggers at the station for computer downloading.

With no runoff entering from outside its catchment, the 2nd Avenue NW SEA Streets site was equipped only with a flow monitoring station at the point where runoff exits the project. This station has a float/shaft encoder with a stilling basin and V-notch weir flow control. In an adjacent yard are a tipping-bucket recording precipitation gauge and a non-recording collector. This site has one data logger. Monitoring at both sites will continue to operate for an undetermined period of time to collect more post-construction data.

Summary of January 2000-January 2001 Results

Viewlands Cascade Drainage System

For the period July 2000 to January 2001, the Viewlands flow monitoring equipment registered a peak upstream flow rate of 3.9 cfs (110 L/s), approximately one-sixth of the anticipated peak flow rate for the 25-year, 24-hour design rainfall event of 25 cfs (708 L/s). Two storms approximated the 6-month, 24-hour storm. The remaining 34 storms fell beneath this level. Due to the relatively low precipitation, assessment of the performance of the swale design based on calendar year 2000 was limited.

Of the 36 individual storms that produced measurable runoff in the Viewlands channel, in 14 cases no inflow reached the downstream monitoring station, almost all presumably having infiltrated the soil. Regardless of soil moisture conditions, the channel retained up to approximately 1,000 ft^3 (28.3 m^3) of runoff, while high retention (75 to 99.9 percent) was achieved for inflow volumes in the range of 1,000 to 3000 ft^3 (28.3 to 85.0 m^3). The cascade system could fully attenuate runoff from an average precipitation depth of 0.22 inch (5.6 mm) during dry soil moisture conditions and 0.13 inch (3.3 mm) during wet conditions. During the dry soil period, 78 percent of the measured inflow infiltrated or was otherwise retained by the channel. Retention dropped to 34 percent during the wet soil period. Over the course of the

July 2000 to January 2001 study interval, the system retained 38 percent of the total inflow. In addition to the hydrologic benefit to Pipers Creek, pollutant mass loading would decrease by at least as much, and most likely more due to contaminant capture in the channel's vegetation and soil. Under the same meteorological conditions, the previous ditch would have infiltrated, at most, an estimated 24,650 ft^3 (700 m^3), or 67 percent less.

2nd Avenue NW SEA Streets

For the March to July 2000 pre-construction period, the 2nd Avenue NW flow monitoring equipment registered a peak flow rate of 0.083 cfs (2.4 L/s), less than one-tenth of the anticipated peak flow rate of 1.5 cfs (43 L/s) for a 25-year, 24-hour rainfall event. Analysis of the storm hyetographs and hydrographs for the 35 storms during the predominantly wet soil moisture conditions indicated a rapid, precipitation-driven runoff response. As a result, the runoff hydrograph closely followed the start, rise, and fall of the precipitation hyetograph.

To put the hydrologic analysis of the baseline 2nd Avenue NW conditions into perspective, runoff volumes were estimated for both a conventional street design and the SEA Streets design. The cumulative measured runoff volume from the existing street was 8601 ft^3 (244 m^3) during the study period of March 11 to July 11, 2000. The conventionally designed road with a curb/gutter/sidewalk system would have generated an estimated 14,806 ft^3 (420 m^3) of runoff under the same rainfall conditions, or 72 percent more. It was estimated that, with a SEA Streets design and the same precipitation, the street right of way would have produced 4989 ft^3 (141 m^3) of runoff. This quantity is 42 percent less than the runoff from the pre-existing street and 66 percent less than from a conventionally designed road.

Precipitation and Flow Analysis from Start of First Full Water Year (October 1, 2000)

Precipitation Analysis

At Seattle-Tacoma International Airport, calendar year 2001 precipitation was close to the long-term mean, while 1999 was above the average and 2000 was 25 percent below. Based on the airport station, wet season (October-March) totals were:

52-y mean—28.7 inches (729 mm);
1999-2000—17.4 inches (442 mm), 61 percent of 52-yr mean;
2000-2001—16.3 inches (414 mm), 57 percent of 52-yr mean; and
2001-2002—31.3 inches (794 mm), 109 percent of 52-yr mean.

Initial monitoring occurred during relatively dry winters. The 2001-2002 winter approximates typical conditions in the region, and thus it provides a better opportunity to assess performance capabilities of the drainage projects.

The October 2000 to March 2001 wet season had two storms approximating the 6-month, 24-hour rainfall event for the region and one that exceeded 24 hours duration and the precipitation total associated with the 1-year, 24-hour event. In contrast, the following winter period had three storms exceeding 24 hours with rainfall between the 6-month, 24-hour and 1-year, 24-hour totals, plus three additional events lasting over 24 hours and exceeding the 1-year, 24-hour total. Since the outset of monitoring, however, there have been no very large storms with infrequent return periods.

Flow Analysis

Viewlands Cascade Drainage System

Rainfall and Runoff Event Summary

Data on the Viewlands drainage system rainfall and runoff were collected for 122 events over the period beginning at the onset of the 2001 water year (1 October 2000) and concluding on 30 April 2002. Seven precipitation events during April, June, and July 2001 are missing from the Viewlands flow record because of flow instrumentation malfunction.

The rainfall statistics demonstrate the distinctions between the wet and dry seasons (e.g. a mean antecedent dry period more than three times as long in the dry compared to the wet season). They also indicate the different characteristics of the two wet seasons represented. The 2001-2002 winter was much wetter overall, with 79 percent more precipitation. Its mean precipitation intensity was 27 percent less, however, because rain was spread over an average storm duration 30 percent longer.

With no infrequent, large rainfalls in the data record, peak upstream flow rate has not yet approached the maximum 25 cfs (708 L/s) estimated for the 25-year, 24-hour event during project design. The peak seen thus far was during a December 2001 storm (4.06 cfs, 115 L/s), also approached during the large summer 2001 event (3.97 cfs, 113 L/s).

Notwithstanding seasonal and annual distinctions in rainfall and rainfall-runoff relations, channel hydrology and hydraulics did not differ as much from wet to dry seasons and between divergent winters. Maximum discharge rate and flow volume reductions from upstream to downstream were similar in the two winters, about 53 percent for rate and 70 percent for volume. These decreases rose to 65 percent for flow rate and 80 percent for volume in the dry season (excluding the large August storm). Average velocity was only slightly higher and minimum hydraulic residence time just marginally shorter in the wetter 2001-2002 winter compared to the preceding year. Dry and wet season average minimum residence time and average velocity differed little.

During the initial study period 14 of 36 events (39 percent) produced no downstream discharge. The initial analysis found that an average precipitation depth of 0.13 inch (3.3 mm) could be fully attenuated during wet conditions (Miller 2001, Miller et al. 2001). This conclusion was also confirmed with more data.

Reductions in peak flows between upstream and downstream were analyzed for three categories of rainfall events: (1) precipitation up to the mean quantity for the region (approximately 0.5 inch, 13 mm), which represents 77 percent of all events in the Viewlands record; (2) precipitation greater than 1 inch (25 mm), approximately half of the 2-year, 24-hour rainfall, the current consensus on the event that can rework stream channels and thus disrupt habitat (9 percent of the recorded events); and (3) wet season (October 1-March 31) events, 86 percent of all the events registered. Downstream peak flows declined from upstream, on average, 65 percent in events up to the mean quantity and 54 percent in wet-season episodes. In contrast, the decrease averaged only 17 percent in the larger, channel-forming events. Therefore, the Cascade project generally helps protect Pipers Creek from the effects of high flows in the winter when it is most vulnerable, although this protection is modest when the potential for channel reforming is highest.

Total Discharge Summary

The new Viewlands drainage system prevented direct release to Pipers Creek of 294,176 ft^3 (8337 m^3) of runoff in the 2001-2002 wet season (33.5 percent of the inflow) and 485,379 ft^3 (13,755 m^3) from October 1, 2000 through April 30, 2001 38.1 percent of the influent). These inflow attenuation percentages are very similar to those registered was in the preceding drier winter and over the earlier full monitoring period. In the wetter winter, though, the volume retained was 2.3 times as large as the winter before.

The Viewlands catchment exhibited runoff coefficients differing greatly between seasons and years. Based on a catchment area of 26 acres (10.5 ha), 17.7 inches (450 mm) of precipitation during the 2000-2001 wet season, and 31.1 inches (790 mm) in the following winter, the runoff coefficient (inflow/rainfall volume) was 16 percent in the first case and 30 percent in the second. Cumulative dry period runoff coefficient was only 8 percent. These results demonstrate the large effect of specific conditions on runoff coefficients and the unreliability of characterizing hydrology with their use.

Hydrograph Analysis

Figures 1 and 2 show hyetographs and hydrographs for two events at Viewlands. Comparisons of the upstream and downstream hydrographs illustrate the roles of antecedent moisture conditions and, especially, precipitation intensity in determining flow attenuation by the Viewlands channel. The event graphed in Figure 1 exhibits substantial peak rate reductions.

In contrast, the other hydrograph shows little attenuation, and even increased downstream rate for a time. This case had intense bursts of precipitation and the highest average intensity in the January 2001-April 2002 study period. It is clear that good performance in flow attenuation strongly depends on having moderate intensities, both during intra-storm intervals and over the full storm. Of course, this pattern generally prevails in Seattle, to the benefit of performance in drainage courses like the Viewlands Cascade.

Comparison with Preceding Ditch

The Viewlands Cascade Drainage System compares quite favorably with the ditch that preceded it. With equivalent meteorology, the ditch is estimated to attenuate through infiltration only about one-third as much flow volume, during

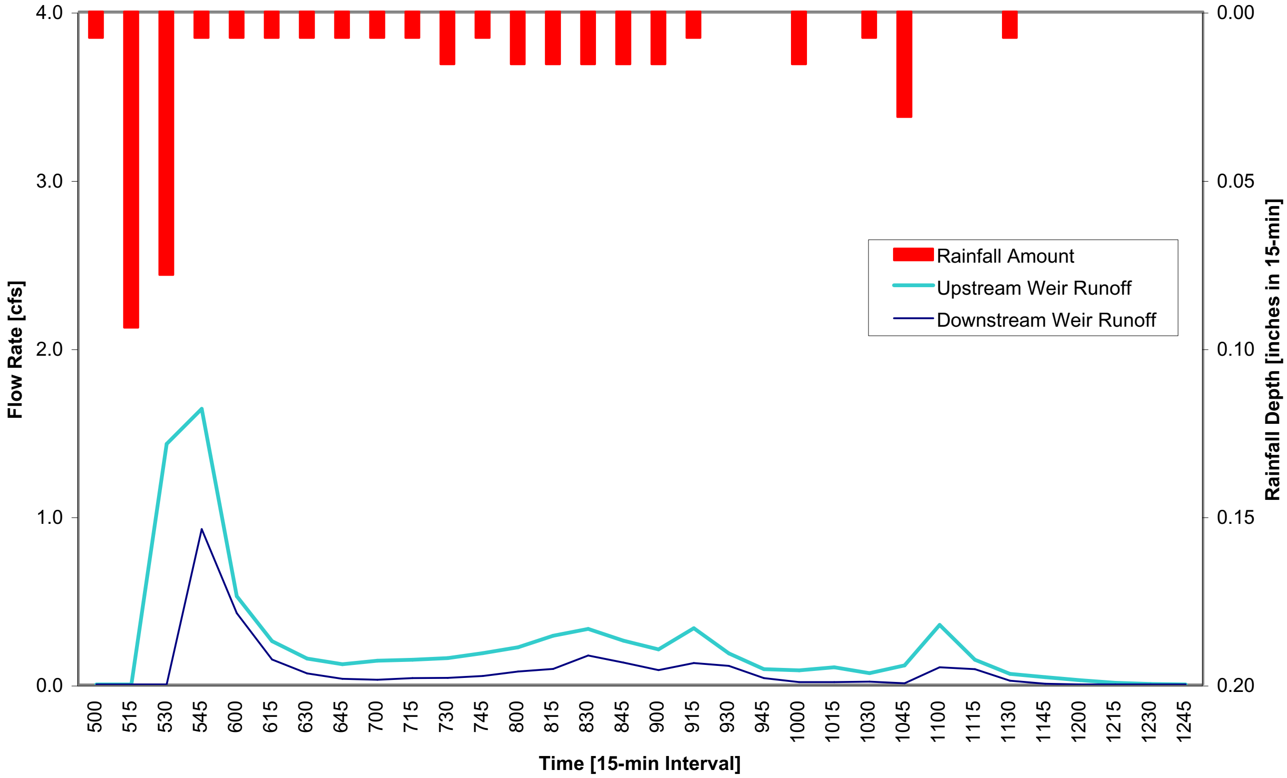

Figure 1. Viewlands Rainfall Hyetograph and Runoff Hydrograph, April 30 (5:00 AM) - April 30 (12:45 PM), 2001.

both dry and wet seasons, under average and maximum conditions, and in total. This uniformity in prediction is an artifact of the simple model used to estimate infiltration from the old ditch but is generally indicative of the different potential recharge in the two cases. The preceding drainage conduit would have released to Pipers Creek approximately 191,000 ft^3 (5413 m^3) of runoff that was retained by its successor during the 2001-2002 wet season and 319,000 ft^3 (9040 m^3) over the course of the current study period.

Average velocities are estimated to be approximately 20 percent higher in the old ditch under the full range of conditions. One of the main reasons for rebuilding in the cascade configuration was to reduce the observed high velocities in the ditch, which resulted in frequent bypass of the downstream drain inlet and erosion of the slope beyond it. The lack of relatively large storms has not provided a real test of velocity reduction yet. Minimum hydraulic residence times are estimated to be about a factor of two longer in the new system compared to the old ditch under most circumstances observed to date, although closer in the two channels in the smallest storms.

2ND AVENUE NW SEA STREETS

Rainfall and Runoff Event Summary

Rainfall and 2nd Avenue NW runoff were monitored during 96 events over the period beginning just after completion of construction (20 January 2001) and concluding on 30 April 2002. As to be expected because of the proximity of the two sites, the rainfall statistics demonstrate the same tendencies as described for Viewlands.

There was never any measured discharge when the estimated precipitation volume was less than 2300 ft^3 (65.2 m^3), representing substantial ranges of the meteorological variables. Thus, it was safe to assume that there was no discharge associated with any unmeasured events below that rainfall volume total. This volume is associated with a rainfall total of about 0.75 inch (19 mm), the runoff from which can apparently be completely attenuated by the storage ponds.

After the SEA Streets project was in place, discharge was measured or estimated for only 10 of the 96 events (10.4 percent). In strong contrast, flow over the weir occurred during all 35 events measured before project construction, even though most were in the drier months. With the new street design there was no dry-season release, even during a storm with the greatest rainfall total on record for the month of August.

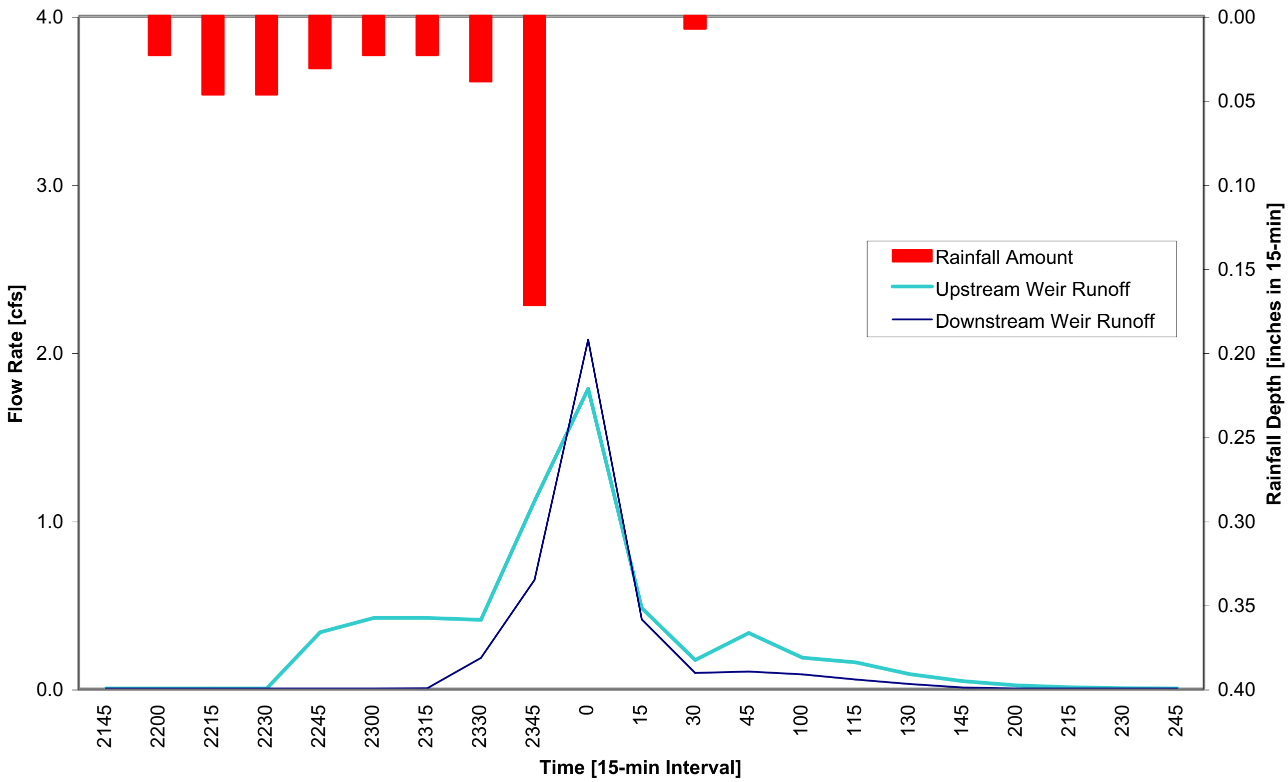

Figure 2. Viewlands Rainfall Hyetograph and Runoff Hydrograph, April 16. (9:45 PM) - April 17 (2:45 AM), 2001.

Even with so few events yielding any discharge, attenuation was so close to complete that the mean flow volume decreases by storm are quite indicative of recharge over the full seasonal and annual periods:

1/20/01-3/31/01 (partial wet season)—	99.1%
4/1/01-9/30/01 (dry season)—	100%
4/1/01-9/30/01 (dry season excluding August storm)—	100%
1/20/01-9/30/01 (partial water year)—	99.6%
10/1/01-3/31/02 (wet season)—	97.6%
1/20/01-3/31/01, 10/1/01-3/31/02 (1 + partial wet season)—	97.8%
1/20/01-4/30/02 (current study period)—	98.2%

Hydrograph Analysis

Figures 3 and 4 show hyetographs and hydrographs for two somewhat contrasting events at 2nd Avenue NW. The early January 2002 storm (Figure 3) followed an antecedent dry period of only 10.3 hours, had average intensity of 0.048 inch/hour (1.2 mm/h), and produced an estimated total precipitation volume of 6635 ft^3 (188 m^3). The later January event (Figure 4) had a much longer antecedent dry period of 94.5 hours and about half the average intensity (0.026 inch/hour, 0.7 mm/h), although it had a brief burst of relatively intense rainfall late in the storm. The total volume estimate was 3418 ft^3 (97 m^3). Durations of the two storms were similar (47.8 and 44.8 hours, respectively).

Discharge occurred much earlier and lasted longer in the first case, with higher soil moisture and overall more intense rain. The extended, light, steady rain through most of the second event produced no discharge, which only occurred suddenly with the precipitation burst. Although the latter storm had less quantity and intensity of rain and lower soil moisture at the beginning, its maximum discharge rate was more than twice the heavier, earlier event (it should be noted, though, that both rates were very low).

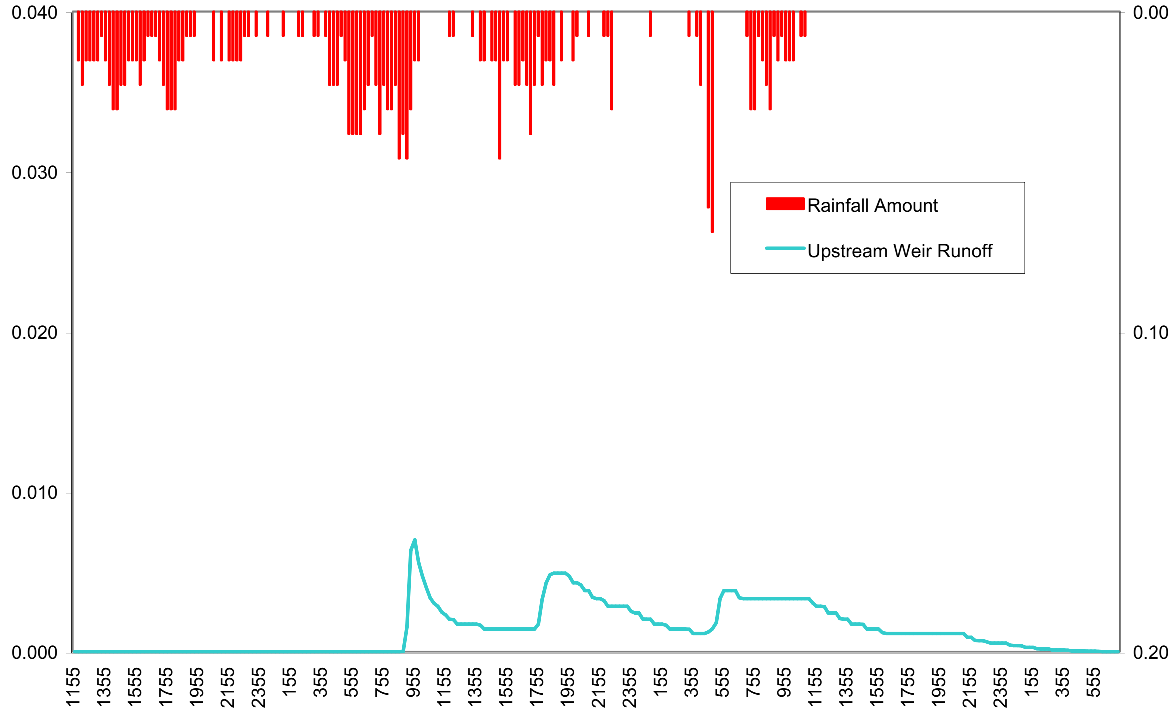

Figure 3. 2nd Avenue NW Rainfall Hyetograph and Runoff Hydrograph, January 6 (11:55 AM) - January 9, (7:25 AM), 2002

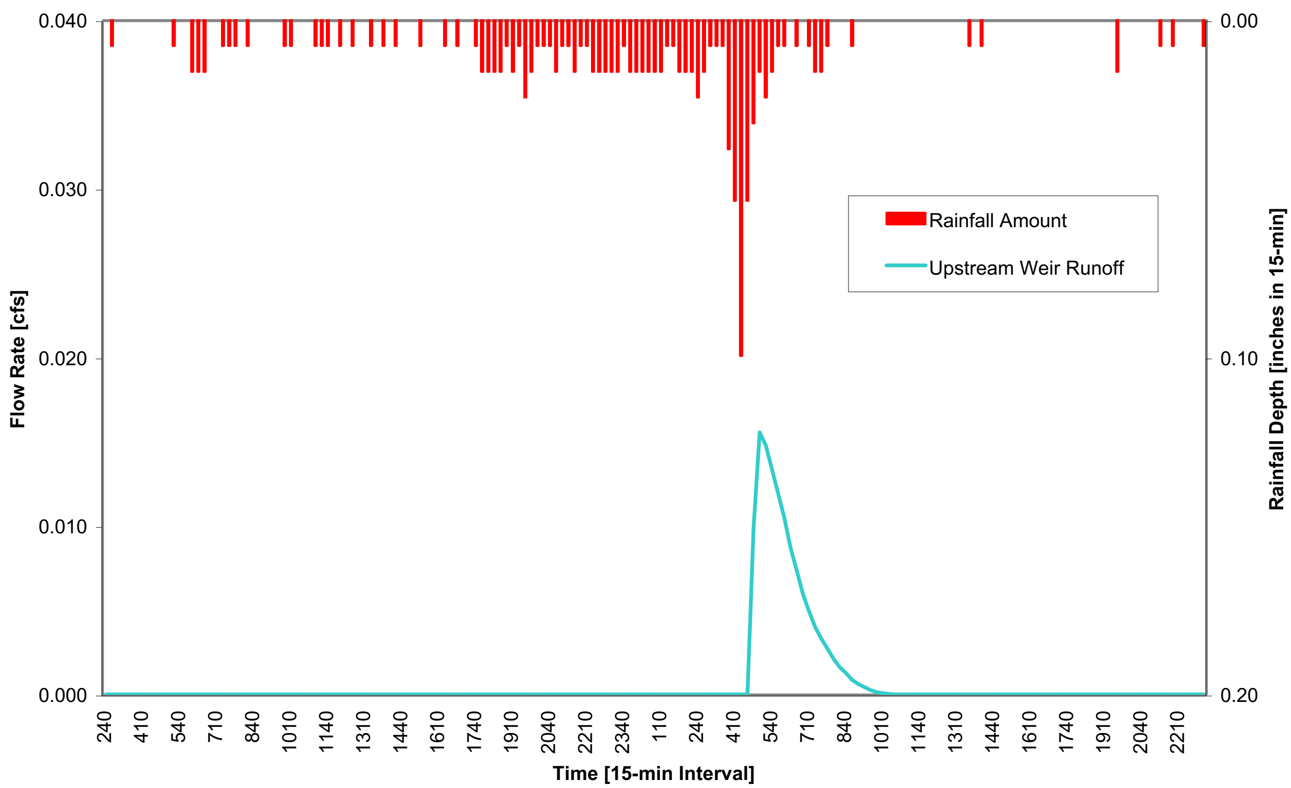

Figure 4. 2nd Avenue NW Rainfall Hyetograph and Runoff Hydrograph, January 24 (2:40 AM) - January 25 (10:10 PM), 2002

Even with the differences in meteorological and soil moisture conditions in the two cases, the SEA Streets runoff mitigation features performed similarly. Runoff quantities were only 4.9 and 3.2 percent of the precipitation volumes falling on the catchment in the respective events. The project has the ability to attenuate all or almost all runoff over a fairly wide range of conditions.

Performance Assessment

The SEA Streets project has exhibited unexpected effectiveness in attenuating runoff, and outcome for which there seems to be several reasons. Prior to construction the glacial till characteristic of the region's soils was exposed essentially at the surface. In site preparation approximately the upper 1 ft (30 cm) of till was removed, amended with compost, and replaced in a loose matrix. This modified soil is apparently offering a substantial water storage volume, most of which was not assumed in project design calculations, as well as helping to effect considerable infiltration, none of which taken into account in design. Therefore, the project is performing so well because it is over-designed by virtue of not being able to forecast well subsurface hydrologic processes with the surface flow hydrologic estimation techniques available during design. In addition to those factors, the project has experienced no rainfall larger than approximately the 1.5-year, 24-hour event and no back-to-back relatively large events. It can be expected that its attenuation ability will drop when an infrequently occurring event challenges with greater precipitation.

Comparison with Preceding Street and Conventional Street Design

The SEA Streets design thoroughly out-stripped the prediction made during the initial study period that it would reduce total discharge from the pre-existing street for equivalent conditions by only 42 percent (Miller 2001; Miller et al. 2001). Precipitation volume retained by a conventional street design is expected to be about 20 percent as great as with the SEA Streets design, and total discharges from the latter configuration are small percentages of those estimated from a conventional streetscape:

1/20/01-3/31/01 (partial wet season)	1.1%
4/1/01-9/30/01 (dry season)	0%
4/1/01-9/30/01 (dry season excluding August storm)	0%
1/20/01-9/30/01 (partial water year)	0.5%
10/1/01-3/31/02 (wet season)	3.0%
1/20/01-3/31/01, 10/1/01-3/31/02 (1 + partial wet season)	2.7%
1/20/01-4/30/02 (current study period)	2.3%

Viewlands Cascade Versus SEA Streets Performance Comparison

This section compares the relative amounts of flow volume reduction achieved with the various drainage system designs discussed above, including: (1) the Viewlands Cascade Drainage System versus the ditch that preceded it, (2) the 2nd Avenue NW SEA Streets project versus the original street drainage system, (3) the 2nd Avenue NW SEA Streets project versus a conventional street drainage system design, and (4) the 2nd Avenue NW SEA Streets project versus the Viewlands Cascade Drainage System. The designs are compared as ratios for dry and wet seasons and overall by normalizing in terms of the runoff volume retained per month. In addition, the Viewlands Cascade and SEA Streets projects are compared in relation to: (1) the runoff volume retained per month and per unit area of contributing catchment as a measure of relative benefit, and (2) the runoff volume retained per month and per dollar of unit area construction cost as a measure of relative cost-benefit.

The benefit ratios for Viewlands Cascade/preceding ditch, SEA Streets/original street, and SEA Streets/conventional street reiterate the points made previously: the improved drainage systems retain several times as much runoff volume as their respective predecessors or, in the case of SEA Streets, the alternative of designing according to the city of Seattle's current convention.

The SEA Streets project attenuates over one-third as much runoff as the new Viewlands channel, even though the SEA Streets project serves less than one-tenth as much contributing catchment area. When placed on an area basis, that advantage multiplies greatly, with retained volume/(month-unit area) being four times as large for SEA Streets compared to Viewlands. The 2nd Avenue NW project has a fractional cost-benefit compared to Viewlands, however, because it cost roughly the same as Viewlands but serves a much smaller catchment. These financial comparisons take no account of potential savings that might be realized with experience and economies of scale in future construction of both project types.

With its position at the discharge of its subbasin, the Viewlands Cascade might be termed a “downstream” solution. Managing runoff at or near its source, the 2nd Avenue NW project site is an “upstream” solution. Its relatively greater unit-area effectiveness is a demonstration of the common observation in stormwater management that acting closer to the source on smaller quantities of water yields better results than downstream intervention. In this case, the unit cost of the upstream project was much higher because of its nature, not its catchment position. Thus, lower cost-effectiveness is not a general drawback of upstream projects. In particular, it would be much more economical to build a streetscape in the SEA Streets style in new construction compared to retrofitting an existing street.

These contrasting strategies can both contribute to protecting stream ecosystems from the damaging effects of high peak flows and volumes if used appropriately. The challenges are to learn how to reduce the cost of the SEA Streets model and then apply an optimal mix of the types based on the objectives sought, opportunities and constraints of the situation, prospective benefits, and costs.

Summary and Conclusions

1. Flow has been monitored at the Viewlands Cascade Drainage System over two full wet seasons, one complete dry season, and a portion of a second one. The 2nd Avenue NW SEA Streets project has received flow monitoring for one full wet season and part of a second one, plus a complete dry season. The wet seasons have differed in meteorological characteristics. The 2000-2001 winter had only 57 percent of the long-term average rainfall. The 2001-2002 winter was slightly above average in total precipitation but had generally low-intensity storms. Neither winter had any very large storms.

2. At both Viewlands and 2nd Avenue NW, flow attenuation by the drainage projects is strongly influenced by rainfall intensity and antecedent dry-period length. Flow reduction, primarily by infiltration, is markedly greater in low-intensity storms compared to high-intensity events, a pattern that is accentuated with relatively low soil moisture attending a preceding dry period of at least a number of days.

3. Over all of the monitoring performed, the Viewlands Cascade has quite consistently reduced the influent runoff volume by slightly more than one-third during the wetter months and overall for the year (the majority of relatively small dry-season flows are attenuated). Also, about one-third of events exhibit no discharge from the end of the channel. It can completely infiltrate about 0.13 inch (3.3 mm) of precipitation and 1000 ft^3 ($28m^3$) of influent regardless of the season or conditions. During the 2001-2002 wet season the new Viewlands channel retained almost 300,000 ft^3 (8500 m^3) of runoff that entered it, preventing its direct release to Pipers Creek and the elevation of erosive flows there. This quantity is nearly three times the amount of retention estimated were the preceding narrow, partially concreted ditch still being in place. The Cascade in the inflow peak flow rate by an average of 54 percent in wet seasons’ storms, although events larger than 1 inch (25 mm) of rain exhibited a lower mean decrease of 17 percent.

4. During monitoring thus far the 2nd Avenue SEA Streets project has prevented the discharge of all dry-season flow and 98 percent of the wet-season runoff. Whereas all events in the baseline-monitoring period, which occurred mostly in the dry season, created a discharge, only about 10 percent have, since the project’s construction. The design can fully attenuate 2300 ft^3 (65.2 m^3) of runoff, which represents the volume produced by approximately 0.75 inch (19 mm) of rain on its catchment. For context, the mean storm quantity at Seattle-Tacoma International Airport is 0.48 inch (12 mm). Based on estimates for a street drainage system design according to City of Seattle conventions, the SEA Streets alternative reduces runoff discharged to Pipers Creek in the wet months by a factor of 4.7 relative to the conventional street.

5. On the basis of unit runoff contributing area, the SEA Streets project is at least four times as effective as Viewlands, depending on how the benefit is computed. However, when normalized in terms of the cost per unit catchment area served, the 2nd Avenue NW reconstruction is much less cost-effective than the Viewlands Cascade.

6. Sufficient data are available now for estimating potential hydrologic benefits of future projects of the Viewlands Cascade and SEA Streets types in similar catchments. These two different techniques can be used in concert in an optimal fashion, especially if costs of the SEA Streets system can be reduced with experience.

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